A 38,000 year History of the Vegetation at Penrith Lakes, New South Wales

Jane M. Chalson[1] and Helene A. Martin[2]

[1] 46 Kilmarnoch St. Engadine, N.S.W. 2233
[2] School of Biological, Environmental and Earth Sciences, University of New South Wales, Sydney Australia 2052 (h.martin@unsw.edu.au)

Chalson, J.M. and Martin, H.A. (2008). A 38,000 year history of the vegetation at Penrith Lakes, New South Wales. *Proceedings of the Linnean Society of New South Wales* 129, 97-111.

Sediments in an abandoned river channel on the flood plain of the Nepean River at Penrith record about 38,000 calibrated years (38 k cal. yr BP) of deposition. Sections of sediments of a 860 cm core proved barren of pollen, but sufficient pollen was recovered from three sections aged about (1) 38-36 k cal. yr BP, middle glacial period, (2) 27-16 k cal. yr BP, middle-late glacial period, including the last glacial maximum and (3) 6 k cal. yr BP to present, late Holocene.

During the 38-36 k cal. yr BP period, the vegetation was an open sclerophyll forest with *Eucalyptus viminalis* and *Leptospermum polygalifolium* prominent. A 'spineless Asteraceae', thought to be *Cassinia arcuata* was prominent in the understorey. *E. viminalis* was the most common eucalypt and it is the most cold-tolerant of the suite of possible eucalypts. During the 27-16 k cal. yr BP period, a shrubland of *Cassinia arcuata* with some grasses was present. The lack of eucalypts during the height of the last glacial period suggests a cold, arid climate and agrees with estimates that the rainfall was about half that of today. In the period 6 k cal. yr BP to present, a *Eucalyptus tereticornis* and *Leptospermum juniperinum* woodland with a grassey understorey occupied the site.

When compared with other records in the Sydney Basin, the vegetation through the last glacial maximum at Penrith Lakes is the only one with a shrubland/grassland community.

Manuscript received 26 February 2007, accepted for publication 24 October 2007

Key words: Climate change, History of the vegetation, Holocene, Last glacial maximum, Palynology, Penrith.

INTRODUCTION

Penrith, situated on the Cumberland Plain, is just east of the Lapstone Monocline which defines the eastern edge of the Blue Mountains Plateau (Bembrick et al, 1980). At Penrith (Figs 1, 2), the Nepean River flows from a confining Triassic sandstone gorge onto shale lowlands where sediments have accumulated since Tertiary times. The Nepean and the Wollondilly Rivers together drain much of the southern part of the Sydney Basin. In the late Pleistocene, it transported abundant gravels over a braided plain. Nanson and Young (1988) use this evidence of exceptional fluvial activity to argue for a pluvial period which ended about 40-45,000 years ago. The river quickly became confined to two stable channels, but the easternmost channel was abandoned about 34-37,000 years ago, leaving only the western channel, the present course of the Nepean River (Nanson and Young 1988).

The gravels have been extracted for building aggregate and the excavations converted into the Penrith Lakes for recreation (Penrith Lakes Development Corporation, 1983/84). A core through the sediments filling the abandoned channel has been used for this study, the base dating from 38 k cal. yr BP. This time span includes the last glacial maximum at about 20-18 k yr ago. There are three other histories of the vegetation extending back to the last glacial maximum in the Sydney Basin: (1) Lake Baraba, one of the Thirlmere Lakes in a confined sandstone gorge (Black et al., 2006), (2) Mountain Lagoon, at 500 m altitude in the Blue Mountains (Robbie and Martin, 2007) and (3) Redhead Lagoon, a now coastal location south of Newcastle (Williams et al., 2006). These studies come from very different environments to that of Penrith Lakes, hence this study will add significantly to our understanding of the history of the vegetation of the Sydney Basin.

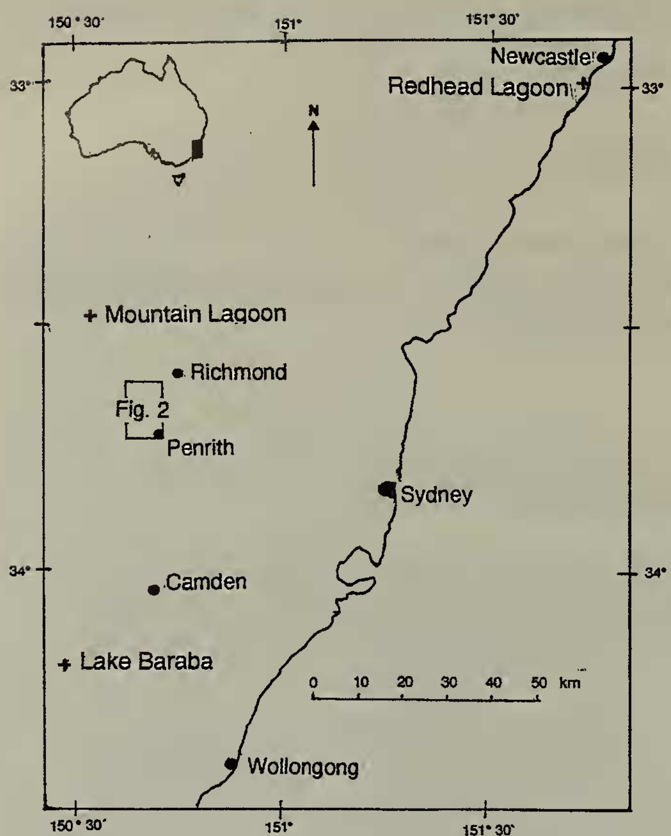


Figure 1. Locality map showing place names mentioned in the text.

THE ENVIRONMENT

The Penrith Lakes site is located on a river terrace of the Nepean River, approximately 4.5 km north of Penrith and 1 km west of Cranebrook Village (Fig. 2), at 33° 42' S and 150° 41' E, and an altitude of 17-19 m asl. The site was a swamp overlying the black clay of the channel fill. The channel cut into the Cranebrook Terrace sediments, which overlie the Ashfield Shale. To the east, is another older and higher terrace of Tertiary origin (Fig. 2).

Evidence of alluvial deposition along the Nepean River extends well back into Tertiary time. Following the Tertiary deposition, the river excavated a broad trench running parallel to the Lapstone monocline, where the Quaternary alluvium of the Cranebrook Terrace is inset (Fig. 3). The thick basal gravels were deposited almost contemporaneously with a sandy clay overburden until the river became confined to two stable channels. Since the easternmost channel was abandoned, the Nepean River appears to have only occupied the western channel and the abandoned channel filled with fine sediments (Nanson et al. 1987). A bedrock bar at the Castlereagh Neck (Fig. 2) isolated the river from eustatic changes and the Nepean River has left no other significant alluvial deposits since the last glacial maximum. However, stripping and replacement of overburden appears to have occurred over the western part of the terrace about 14 k yr BP (Fig. 3).

Before gravel extraction commenced, the swamp collected runoff from the west and southwest, draining the entire region between the levees of the Nepean River. Water gradually passed through the swamp and eventually entered a small tributary of Cranebrook Creek to the north of the swamp. The swamp acted as a sump during times of low runoff but as a drainage channel during periods of higher runoff (Chalson 1991).

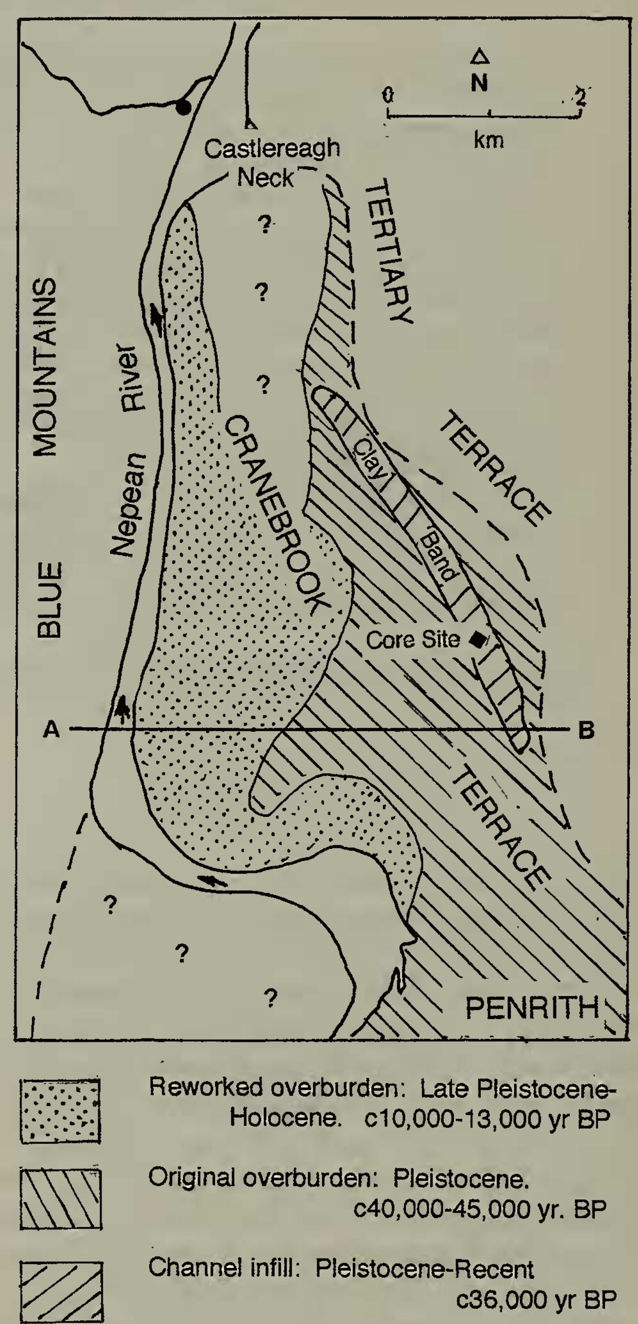


Fig. 2. The Cranebrook Terrace, showing the alluvial formations and the location of the core site. The cross section A-B is shown in Fig. 3. Modified from Nanson et al. (1987)

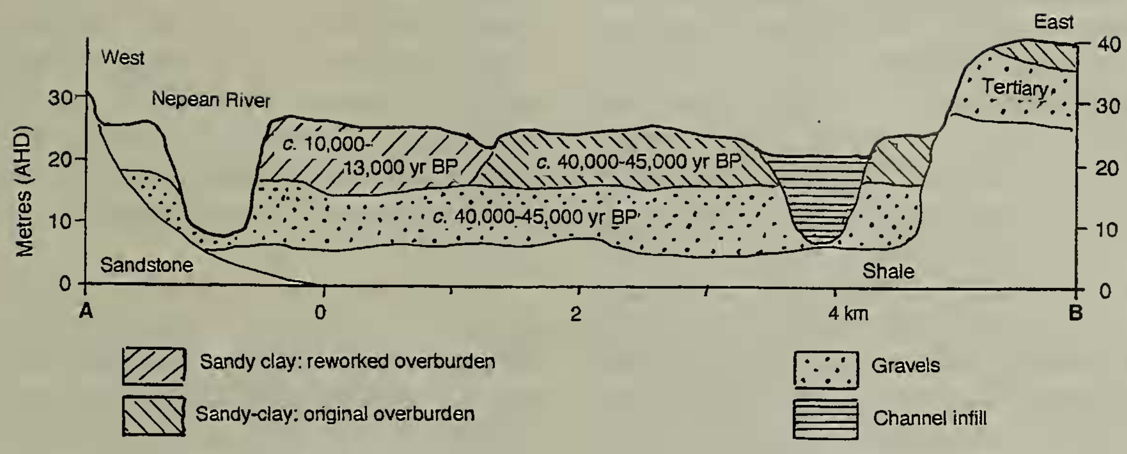


Figure 3. Cross section of the Cranebrook Terrace, showing the alluvial units. For location of cross section, see Fig. 2. Modified from Nanson et al. (1987)

The soils of the Cranebrook Terrace are weakly differentiated on the alluvium of the western side near the river, where the sediments were deposited 9,000-12,000 years BP. On the eastern side, where the sediments are some 38,000 years old, deep weathering has produced strongly differentiated profiles. The soils are red and yellow podzolics with complex variability (Young et al. 1987).

The closest currently operating meteorological station is at Richmond on the University of Western Sydney, Hawkesbury campus, some 20 km NNE of Penrith and at a similar altitude. Here, the mean annual rainfall is 800 mm pa, with January to February the wettest months with an average of 89-96 mm per month and July to September the driest months, with an average of 43-47 mm per month. The mean daily maximum annual temperature is 23.9°C, with a mean daily maximum of 28.9-29.4°C for the hottest months of January-February. The mean daily minimum annual temperature is 10.5°C, with a mean daily minimum of 3.2-4.4°C for the coldest months of July-August (BoM 2006).

A meteorological station at Penrith, not operating now, recorded a long term mean annual rainfall of 685 mm pa (Bureau of Meterology 1966) and a short term record at Penrith Lakes, 687 mm pa (Chalson 1991).

A survey of the vegetation in the Penrith area (Benson, 1992) found that very little of the natural vegetation remains because of the suitability of the soils for agriculture. The vegetation patterns relate strongly to the underlying geology with major groups of communities being restricted to either the Wianamatta Shale, Tertiary alluvium, Holocene (and other Quaternary) alluvium or Hawkesbury Sandstone (Benson, 1992). The swamp surface had the most significant natural vegetation remaining in the area (Chalson 1991).

Melaleuca linariifolia tall shrubland with *Eleocharis sphacelata*, *Typha orientalis* and *Philydrum lanuginosum* covered the swamp, with *Triglochin procerum* in shallow standing water. *Juncus usitatus* and *Persicaria* spp. were common in waterlogged areas (Benson 1992). The southern end of the swamp was almost completely covered with *Carex appressa* and occasional *M. linariifolia*, with *Melaleuca styphelioides* in deeper water. Midway along the swamp, *M. linariifolia* was associated with *Paspalum distichum*, *C appressa*, *T. orientalis* and *T. procerum*. Toward the northern part of the swamp, *P. distichum* and *E. sphacelata* were dominant, with *C. appressa* and *J. usitatus* in the marginal areas. *M. linariifolia* is still found at the northern extreme of the swamp (Chalson 1991).

Only small patches of dryland vegetation remained on the river flats, and from the flora of these patches, together with early botanists' reports, some idea of the original vegetation may be achieved (Benson 1992). *Casuarina cunninghamiana* was found in these remnant sites, and would have fringed the river. *Acacia* spp., *Bossaiea rhombifolia*, *Pultenea flexilis* and *Kennedia rubicunda* may have been present in the understorey. The floodplain once supported a river flat open forest with *Eucalyptus amplifolia* and *Angophora subvelutina* dominant. A remnant of open forest east of the swamp had *E. amplifolia*, *E. baueriana*, *E. eugenioides* and *E. moluccana* (Chalson 1991). *Eucalyptus tereticornis* was predominant downstream around Richmond. The Tertiary alluvium supported remnants of *E. fibrosa* open forest and the Ashfield Shale supported *E. crebra* and *Syncarpia glomulifera*. Understorey species found in these remnants were *Bursaria spinosa*, *Themeda australis*, *Aristida ramosa*, *Daviesia ulicifolia* and *Grevillea juniperina* (Benson, 1992).

For thousands of years, the Penrith Lakes area was extensively used by the original inhabitants, the Darug people (Penrith Lakes Development Corporation 2006). Most of the preserved sites are surface middens on the river terraces and are probably less than 3,000 years old. Stockton and Holland (1974) found stone implements in the gravels at 9 m depth and obtained radiocarbon dates of 27,000 BP, but Nanson et al. (1987) regard this as contamination since all of the gravels were deposited by 47,000-45,000 BP. However, stone artifacts have been found in the tumble at the foot of the quarry, and since all of the overburden was removed before quarrying the gravels, the possibility of contamination is remote. The wear on the artifacts suggest that they were dropped close to the site where they were found (Nanson et al. 1987).

Excavation of the Shaws Creek KII rockshelter (Kohen et al. 1984) has revealed more than 13,000 years of occupation. This site, close to both mountane, riverine and plain environments would have enabled access to an abundance and variety of plants and animals. The gravels and boulders in the bed of the river would have supplied a variety of rock types for stone implements. There is an older phase of relatively sparse occupation and a younger phase of seemingly more intense occupation associated with a change in stone tool technology about 4,000 BP (Kohen et al. 1984).

Europeans settled in the region shortly before 1800 AD and settlement accelerated between 1801 and 1806. Initially, settlement focused on timber getting and by 1810, the cedar and rose mahogany had been cleared. Subsequently, the settlers began to grow wheat from around 1801 until the 1820's when this was replaced by grazing, probably due to falling fertility. In the late 1800's, market gardens and dairying developed to cater for the Sydney market (Chalson 1991). The entire site has been extensively altered since 1991 by the extraction of building aggregate and subsequent construction of the Sydney Olympic Games rowing course. Very little evidence of the original clay channel remains today.

METHODS

The core site was located where it was thought that the sediments of the abandoned channel would be the deepest. The top 20 cm was a dense fibrous mat that had to be trenched. From 20 cm to 50 cm, the sediments were hand-cored, using a Russian D-corer (Birks and Birks 1980). From 75 cm to 860 cm, a continuous core of 50 mm diameter was obtained using a drill truck kindly provided by the Penrith Lakes Development Corporation. Samples for pollen analysis were taken at 10 cm intervals. The uppermost sample for radiocarbon dating was taken from the trench and the other samples were taken from the core at postulated zone boundaries and at the base of the core. A kilogram or more of the clay was required for each radiocarbon sample.

Very little of the natural vegetation remains around Penrith (Benson 1992), hence it was not surveyed. An initial survey of surface samples from degraded remnant stands showed that the pollen was poorly preserved and contained over 50 % Poaceae, reflecting the disturbed nature of the vegetation. Hence the present day pollen deposition was unlikely to assist in interpretation of the core pollen spectra, however a study of pollen deposition in natural vegetation across the Blue Mountains (Chalson 1991) may give some insight for interpretation, although the environments of these sites are somewhat different to the Penrith site.

Pollen preparations extracted from the core sediments were spiked with of a known concentration of *Alnus*, then treated with hydrochloric and hydrofluoric acids to remove siliceous material (Birks and Birks 1980), oxidised with Schultz solution (a saturated solution of potassium perchlorate in nitric acid), cleared in 10% potassium carbonate and the residue was mounted in glycerine jelly (Brown, 1960). Reference pollen was treated with standard acetolysis (Moore et al. 1991).

Pollen was identified by comparing grains from the core with reference pollen. Special attention was paid to pollen of the Myrtaceae which was identified following the method in Chalson and Martin (1995). Poaceae was extremely abundant in some of the samples and several different types could be recognised (Appendix 1), although they could not be identified with any taxon within the family.

Grains were counted along transects across the slides and tests showed that a count of more than 140 grains adequately sampled the residues. The counts were presented as percentages of the total count and pollen concentrations were calculated for the most important taxa.

The abundance of charcoal retained after sieving was estimated subjectively on scale of 1 to 8. Counts of microscopic charcoal for a swamp at Kings Tableland showed that the two methods gave similar results, although the latter was more variable (Chalson 1991).

Table 1 The sediments. The Troels-Smith method of description (Birks and Birks 1980) has been followed.

Depth (cm)	Sediment type	Colour
Trench		
0-15	Rooty peat	Olive grey, greyish brown, yellowish brown
16-20	Peaty clay	Brown/dark brown
Hand core		
21-50	Clay	Dark grey, greyish brown, dark brown, pale brown
51-74	No core recovery	
Drill core		
75-90	Clay	As for 21-50 cm
91-280	Clay	Grey, dark grey, greyish brown, yellowish brown, with a few mottled bands
281-570	Clay	Mottled grey, light grey, brown, pale brown, yellowish brown
571-660	Clay	Grey, light grey, brown, pale brown, yellowish brown, olive brown, with a few mottled bands
661-760	Clay	Brown, yellowish brown, olive grey.
761-860	Silt, silty clay	Greyish brown, dark grey, grey, dark yellowish brown

RESULTS

The core revealed some 20 cm of rooty peat at the top, then clay down to 760 cm, and finally silt and silty clay down to the base of the core at 860 cm (Table 1). The colour of the clay is predominantly grey and greyish brown, with some dark grey and yellowish brown colours. There are minor bands of mottling below 91 cm and consistent mottling between 281 cm and 570 cm. The radiocarbon dates are presented in Table 2 and show that the record extends back approximately 38,000 calibrated years BP (38 k cal. yr BP).

Clay usually has a lower pollen content than peat, having been deposited in a lake where pollen must be transported to the site, whereas with peat, the plants growing on site contribute pollen directly into the sediments. Mottling indicates a fluctuating water table which is destructive to pollen. There are several sections in the core which failed to yield workable pollen spectra (Fig. 4). Nevertheless, sufficient pollen has been recovered to provide a history of the vegetation for certain periods and to illustrate changes in the vegetation over time.

In sediments such as these, the possibility of differential pollen destruction must be addressed. Cyperaceae and Poaceae are thin-walled and fragile grains, and may be expected to be destroyed first. The pollen spectra from the clays have a proportion of these fragile grains and are thus are no different from

Table 2. Radiocarbon dates (standard C14 technique) on bulk samples (see Methods). Calibrated years have been calculated according to the Radiocarbon Calibrated Program Calib Rev 5.0.2 (Stuiver and Reimer, 1985-2005).

Depth (cm)	Laboratory number	Age (radiocarbon years) (yr BP)	Calibrated years BP (cal. yr BP)
40-45	SUA-2489	280 ± 50	1,650
410-440	SUA-2349	11,140 ± 200	11,150
795-830	SUA-2490	33,500 ± 700	39,100
830-857	SUA-2350	32,000 ± 500	37,600

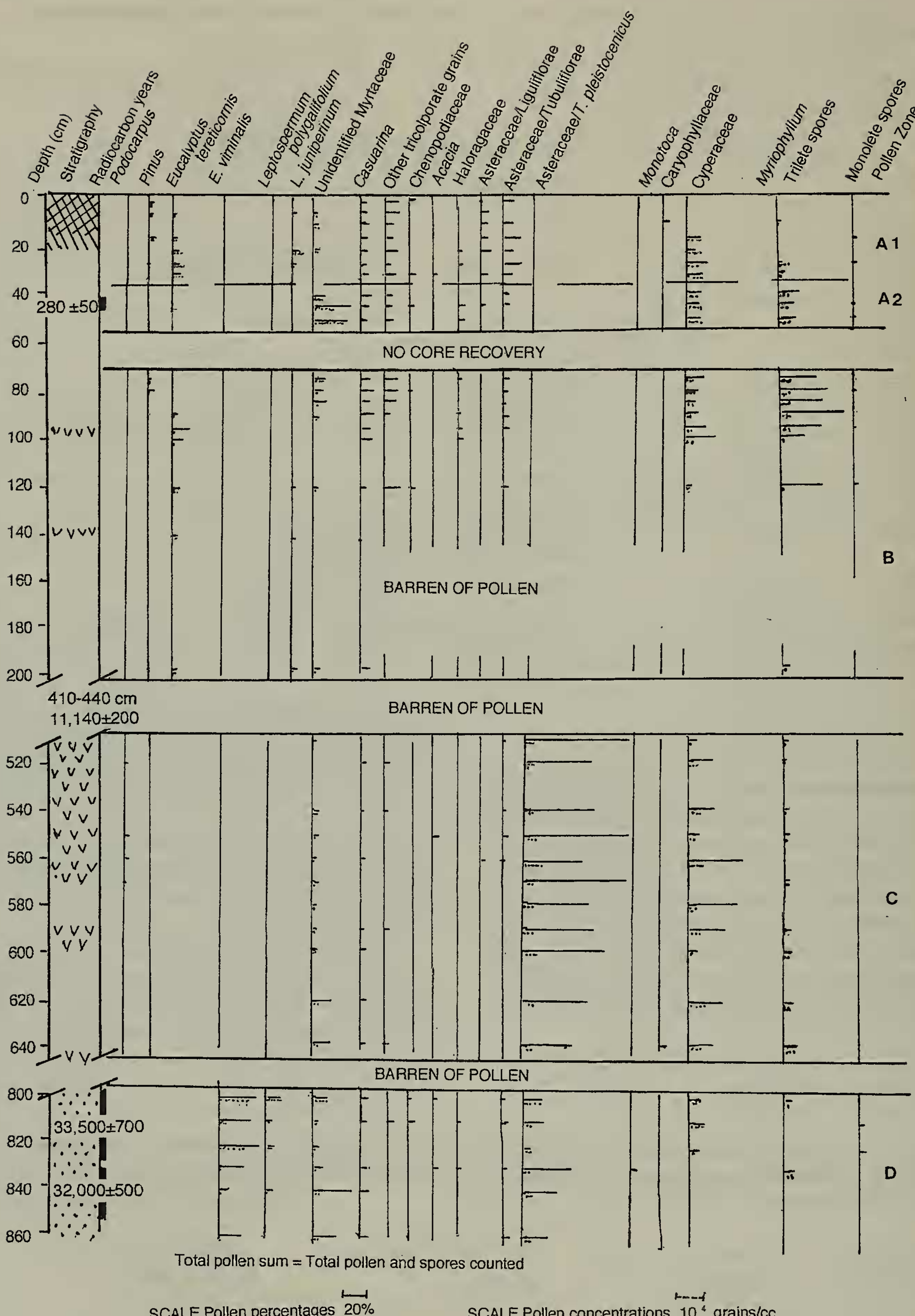
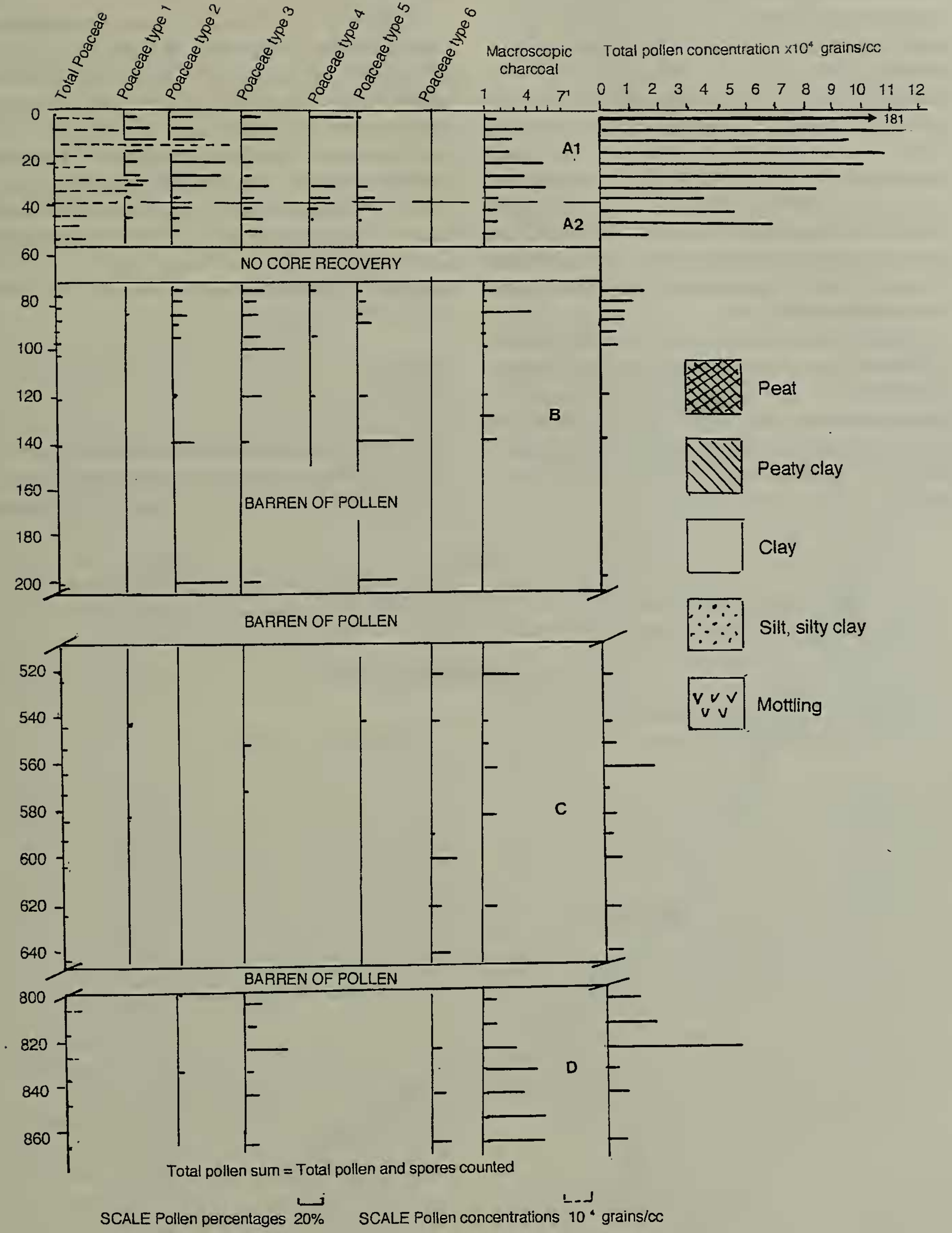


Figure 4 (above and opposite). Pollen diagram. The upper solid line represents percentages and the lower broken line the pollen concentrations. For species included in the pollen type name, see Appendix 3. [1]Subjective scale for macroscopic charcoal, the higher the number the more charcoal: see Methods.


Total Poaceae
Poaceae type 1
Poaceae type 2
Poaceae type 3
Poaceae type 4
Poaceae type 5
Poaceae type 6
Macroscopic charcoal
1 4 7
Total pollen concentration x10⁴ grains/cc
0 1 2 3 4 5 6 7 8 9 10 11 12
181
0
20
40
60
80
100
120
140
160
180
200
520
540
560
580
600
620
640
800
820
840
860
A1
A2
B
C
D
NO CORE RECOVERY
BARREN OF POLLEN
BARREN OF POLLEN
BARREN OF POLLEN
Peat
Peaty clay
Clay
Silt, silty clay
Mottling
Total pollen sum = Total pollen and spores counted
SCALE Pollen percentages 20%
SCALE Pollen concentrations 10⁴ grains/cc

the spectra from well preserved sediments.

The pollen spectra are presented in Fig. 4. and the taxa represented by the name on the pollen diagram are found in Appendix 3. Percentages for all taxa identified and pollen concentrations for the most abundant taxa are shown. The total pollen concentration is high at the top, then low through the clay with some high concentrations in the basal silt and silty clay. When total pollen concentrations are high, concentrations of individual taxa generally parallel percentages, but when the total is low, individual concentrations remain low, even though percentages may be high, a reflection of the relative nature of the percentages.

The pollen spectra have been zoned as follows (Fig. 4), and an age model has been deduced from Fig. 5, assuming a uniform rate of sediment deposition. The sediments are relatively uniform throughout the core and accumulation has probably been similar to today, where the abandoned channel acts as a drainage sump.

Zone D, 860-790 cm, c.38 to 36 cal. yr BP (see Fig. 5).

Total pollen concentration is low but increases towards the top of the zone. *Eucalyptus viminalis* and *Leptospermum polygalifolium* are prominent here and the *Casuarina* content is low. There are moderate amounts of Asteraceae/Tubuliflorae and the form species *Tubuliflorites pleistocenicus*, which probably represents the shrubby *Cassinia arcuata* (see Appendix 2). Other sclerophyllous shrubs, e.g. *Acacia*, Haloragaceae and *Monotoca* are present also. Poaceae types 3 and 6 are present, with minor amounts of Cyperaceae towards the top of the zone. There is also a large amount of charcoal.

790-650 cm, c. 36.5 to 27 k cal. yr BP, barren of pollen.

Zone C, 650-500 cm, c. 27 to16 k cal. yr BP.

Total pollen concentration is low throughout the zone. Myrtaceae pollen is too degraded for specific

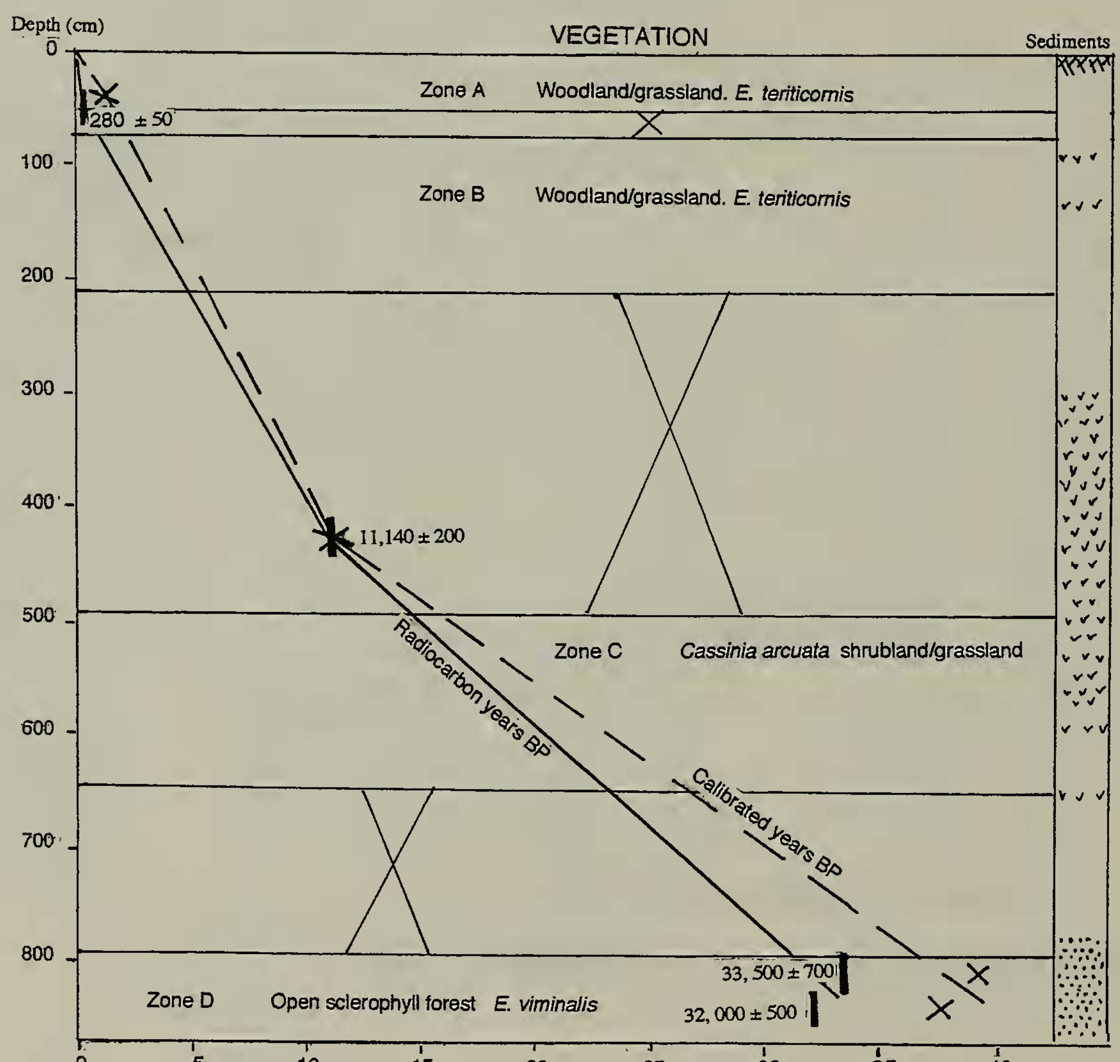


Figure 5. Summary diagram of the history at Penrith Lakes. This model assumes continuous deposition (see text). For legend of sedimentary symbols, see Fig. 4. Radiocarbon dates are shown here, and for calibrated dates, (crosses), see Table 2.

identification, and there is far less of it than in the zone below. The shrubby *T. pleistocenicus* is the most prominent pollen type, there are some Poaceae, especially type 6, and Cyperaceae is more abundant than in the zone below. *Podocarpus* is usually present and has the most consistent representation for the profile. The vegetation of this zone, which includes the last glacial maximum, would have been predominantly shrublands with few *Eucalyptus* spp. Charcoal content is low, with the exception of one higher value.

500-220 cm, c. 16 to 6 k cal. yr BP, barren of pollen.

Zone B, 220-75 cm, c. 6 to 2.2 k cal. yr BP.

Total pollen concentration is low in the lower part of the zone, but increases towards the top. *Eucalyptus tereticornis* and *Leptospermum juniperinum* are present here and there is an increase in *Casuarina*, although it is not large. The shrubby *T. pleistocenicus* is completely lacking, Poaceae types 2, 3 and 5 are more abundant, but type 6 is not present. Cyperaceae and trilete fern spores increase towards the top of the zone. The 'other tricolporate grains' group, probably representing herbs and shrubs, is consistently present in the upper part or the zone. Most of the charcoal values are low.

75-55cm, c. *2.2 to 2 k cal. yr BP*, no core recovery.

Zone A, 55 cm to surface, c. *2 to 0 k cal. yr BP.*

Zone A has high pollen concentrations, especially in the peat, and is subdivided into two sub-zones, A2 and A1. The major contributors to A2 sub-zone are Myrtaceae, Poaceae, Cyperaceae and the trilete spore group. Unfortunately, the poor preservation does not allow identification of the *Eucalyptus* species in the older Subzone A2.

In Subzone A1, *Eucalyptus tereticornis* and *Leptospermum juniperinum* are prominant. The other tricolporate grains group (shrubs and herbs) and Asteraceae/Tubuliflorae type have increased. Asteraceae/Liguliflorae is consistently present through the sub-zone. Poaceae has increased, especially types 1 and 2 and the Cyperaceae content is maintained. The introduced *Pinus* occurs here and the charcoal content is high.

HISTORY OF THE VEGETATION

The abandoned river channel would have been a lake or pond for almost the entire time, becoming a swamp supporting rooted vegetation for probably only a few hundred years (see Fig. 5) prior to the present. The lake was probably quite shallow, subject to drying out on occasions of long dry spells. The fluctuating water table would not have favoured pollen preservation, hence there are long sections of the profile with no pollen and thus no record of the vegetation.

he periods where there is a record of the vegetation (Fig. 5) show that from about 38 to 37 k cal. yr BP (zone D), *Eucalyptus viminalis* was dominant, with minor *Casuarina* and some *Leptospermum polygalifolium*. If the total Myrtaceae pollen of this zone is compared with the top part of the profile, which is assumed to represent the modern vegetation, then *Eucalyptus* species, presumably the tree cover, would have been greater than in the modern vegetation. Sclerophyllous shrubs were present in the understorey, particularly *Cassinia arcuata* which colonised disturbed sites (see Appendix 2). There would have been some grasses and a few Cyperaceae, the latter probably fringing the lake. The vegetation was probably an open sclerophyllous forest.

During the period 26 to 16 k cal. yr BP (zone C), which includes the last glacial maximum, the vegetation was predominantly a shrubland/grassland, with the shrub *Cassinia arcuata* dominant, and minimal trees. Some grasses were present and they are the same types as found in the older zone below. Cyperaceae was more abundant than in the preceding zone.

By the period 6 to 2.2 k cal. yr BP (zone B), some trees had returned, with *Eucalyptus tereticornis* and *Casuarina* suggesting an open woodland, particularly in the upper part of the zone. The shrub *Cassinia arcuata* had disappeared entirely. Grasses were more common, but the types found in the Holocene are mostly different to those on older zones, showing that the grass flora had changed. Trilete fern spores are far more abundant, suggesting a moister environment.

After 2 k cal. yr BP, the increased Myrtaceae pollen content suggests that the tree cover may have increased, but preservation is too poor to identify the species in Zone A2. In the younger Zone A1 *Eucalyptus tereticornis* has been identified, but it decrease towards the top of the profile, most likely due to European wood cutting. Grasses are more abundant and the uppermost levels would have included agricultural and introduced grasses and herbs. Trilete spores decrease, especially in the upper Zone A1.

The charcoal content is consistently higher in the basal Zone D and the top Zone A. The higher content may indicate more fires, but alternatively, it may indicate more fuel to burn. Zone D has the greatest tree cover, hence more fuel is likely. The tree cover is less in Zone A, but this period encompasses European settlement which may have been the cause of greater burning. There are high charcoal values at a few other levels in the core, but overall the content is low between these two zones.

CLIMATIC HISTORY

The climatic parameters for the tree species in the region today and identified in the sediments (Table 3) give some basis for deducing climatic changes at Penrith. *Eucalyptus viminalis* has the lowest of the mean minimum temperatures for the coldest month, hence is the most cold tolerant, and is predominant in the period 38-36 k cal. yr BP, suggesting that temperatures were lower than today. The tree cover was probably greater than the present-day, suggesting better effective soil moisture. Even if rainfall was the same, the cooler temperatures would ensure more effective moisture. This study concurs with previous studies (reviewed by Allan and Lindesay, 1998; Pickett et al., 2004) which indicate cool and moist climatic conditions about 32 k yr BP, with temperatures some 2.5 °C lower than today.

The period 26-16 k cal. yr includes the last glacial maximum. The vegetation was shrubland, suggesting that temperatures and rainfall was less than the minimum required by the tree species (Table 3). Other episodic events, for example, extreme frosts or drought, may have contributed to keeping the river flats treeless (Hope, 1989). Previous studies indicate that the period 25 to 20 k yr BP was colder and drier, with temperatures some 3-5 °C lower than today. During the last glacial maximum (*c.* 18 k yr BP), rainfall was up to half of present day values and air temperatures were as low as 7-8 °C below present, and winds were some 20 % stronger (Allan and Lindesay, 1998). This study is thus in accord with previous studies.

The transition period from glacial maximum to the Holocene, when temperatures and rainfall increased to more like the present, is missing from this record. In the early Holocene (*c.* 9-6 k yr BP), the climate was wetter than today and the late Holocene appears to have been drier than the early Holocene with less dramatic changes (Allan and Lindesay 1998, Pickett et al. 2004).

Trees had returned to the river flats by 6 k cal. yr BP, but their density was not as great when compared with the period 38-36 k cal yr BP. The tree species in this younger period are different as well.. Grasses increased, but it was a different suite of species. There was a much increased fern component, suggesting wetter conditions, at least around the abandoned channel. Grasses increased further and trees decreased towards the present, probably due to the influence of European settlement.

These climatic interpretations follow the overall trends expected from previous studies, but moisture relationships would have been the result of both rainfall and river activity which at times may have augmented or subtracted moisture from the site. It is unknown how much influence river activity would have had on the moisture relationships, but climatic change would have had an effect on river discharge also.

Table 3. Climatic parameters of some of the tree species found in the Penrith area (Benson, 1992), from Boland et al (2002). P, found in the area today. F, found as a fossil in the core. Present day climatic averages are included for Richmond, the nearest operating meteorological station and the mean annual rainfall for Penrith (see text).

Species	Mean max. temp, hottest month, °C	Mean min. temp., coldest month, °C	Max no. frost days per year	Mean annual rainfall, mm
Penrith	n/a	n/a	n/a	686
Richmond	28.9-29.4	3.2-4.4	n/a	800
Casuarina cunninghamii [1] P, F	25-40	0-15	>50	500-1500 [1]
Eucalyptus eugenioides, P	25-33	0-6	>50	700-1100
E. moluccana P	26-32	0-10	>50	700-1200
E. tereticornis P, F	24-36	1-19	30	630-3000
E. viminalis F	20-32	-4-8	0-100	500-2000

[1]A riverine species, hence rainfall alone is no indication of available moisture

DISCUSSION

The Penrith Lakes history may be compared with other records in the Sydney Basin. At Lake Baraba near Thirlmere (Fig. 1) (Black et al. 2006), lacustrine clays were being deposited from >43 k yr BP until the early Holocene, when peat deposition started about 8 k yr BP. Bands of oxidised sediments suggest lake level fluctuations, hence the depositional environment was generally similar to Penrith Lakes, except for the different dates of the onset of peat deposition. Unlike Penrith Lakes, however, the vegetation at Lake Baraba was a Casuarinaceae woodland/shrubland which remained relatively stable from >43 k yr BP, through the glacial maximum until the early Holocene, when Myrtaceae expanded at the expense of Casuarinaceae (Black et al. 2006). Lake Baraba is set in a sandstone gorge and it may have been sufficiently protected to function as a refugium for woodland during the last glacial maximum.

Mountain Lagoon, at about 500 m altitude in the Blue Mountains (Robbie and Martin 2007) has a 23 k cal. yr BP record. The lagoon was a lake initially, but peat formation started about 20 k cal. yr BP. Both Casuarinaceae and Myrtaceae were prominent in the vegetation throughout the whole time. While the species of *Eucalyptus* changed with time, a few species were present the whole time, so some tree species survived the glacial period. The vegetation was thus remarkably stable through the climatic changes of the glacial period. The reason for this stability may lie in the favourable moisture relationships. If, during the last glacial maximum, the rainfall of Mountain Lagoon was just 50% of the current rainfall, it would have been about the lower limits required by some of the *Eucalyptus* species, hence they could remain at the site. The location of Mountain Lagoon is sheltered, hence moisture relationships would have been further enhanced (Robbie and Martin 2007). Half the current rainfall at Penrith Lakes (Table 3), however, would have been less than the lower limits required by all of the *Eucalyptus* species identified. Also, moisture relationships of the open floodplain site of Penrith Lakes would not be so favourable.

At Redhead Lagoon, south of Newcastle (Fig. 1), the sedimentary record goes back some 75 k cal. yr BP (Williams et al. 2006). At 40 k cal. yr BP, there was an increase in Poaceae and a decline in woody taxa, reflecting drier times. At the height of the last glacial period, Casuarinaceae was prominent and *Angophora/Corymbia* and *Eucalyptus* were present also, hence the glacial maximum was not treeless at this site. There was an increase in the shrubby taxa *Monotoca*, Proteaceae and Asteraceae, including the spineless Asteraceae *T. pleistocenicus* (Williams 2005) also found in this study. Overall, the vegetation communities were less complex during the last glacial maximum when compared with those of today, indicative of a harsh dry environment (Williams et al. 2006)

Each of these four sites in the Sydney Basin represents a different environment and each has its own distinctive vegetation and pattern of change through the last glacial maximum. The Penrith Lakes site is the only one that would have been a treeless shrubland.

CONCLUSIONS

This study reveals periods of three different kinds of vegetation on the river flats at Penrith in successive times:

1) During 40-36 k cal. yr BP, a *Eucalyptus viminalis*, *Leptospermum polygalifolium* open sclerophyllous forest with a shrubby understorey of predominantley *Cassinia arcuata* and a few grasses.

2) During 27-16 k cal. yr BP, a *Cassinia arcuata* shrubland, with Cyperaceae, probably fringing the abandoned channel, and few grasses.

3) During 6 k cal. yr BP to present, a *Eucalyptus tereticornus*, *Leptospermum juniperinum* grassy woodland with Cyperaceae and ferns, the latter probably closer to the abandoned channel. The grass flora here would have been substantially different to that in the older periods recording the vegetation.

The pollen frequencies suggest that the tree cover of the oldest *E. viminalis* vegetation unit was greater than the youngest *E. tereticornis* unit. The higher percentages of Poaceae in the younger unit would depress the percentages of *E. tereticornis*, but pollen concentrations of the *E. tereticornis* are low also, in accord with the percentage evidence and a lesser tree cover.

The climatic interpretations follow the general trends of other studies: colder and drier during 40-36 k cal. yr BP, colder and drier still during 27-16 k cal. yr BP, then warmer and wetter from 6 k cal. yr BP to the present. The peak in fern spores infer that 3-2 k cal. yr BP was the wettest period hydrologically, which may have been climatic, but river activity and altered drainage may have affected the local moisture relationships.

The vegetation through the last glacial maximum at other sites in the Sydney Basin was specific to each site. Penrith Lakes is the only one which would have been a treeless shrubland.

ACKNOWLEDGEMENTS

We are indebted to the Joyce W. Vickery Research Fund of the Linnean Society of NSW, the River Group Fund of the Federation of University Women, and the Penrith Lakes Development Corporation for financial assistance with this project. Our thanks go to Dr. John Turner, Dr. Mike Barbetti, the National Parks and Wildlife Service of NSW and the Forestry Commission of NSW for assistance. To the many friends, relatives and colleagues who gave unstinting help and encouragement, our heartfelt gratitude.

REFERENCES

Allen, R. and Lindesay, J. (1998). Past climates of Australasia. In: 'Climates of the Southern Continents' (Eds J.E. Hobbs, J.A. Lindesay, H.A. Bridgman) pp. 208-247. (Wiley & Sons, Chichester).

Bembrick, C., Herbert, C., Scheibner, E., Stuntz, J. (1980). Structural subdivision of the Sydney Basin. In 'A Guide to the Sydney Basin' (Eds C. Herbert and R. Helby) pp 3-9. (Department of Mineral Resources, Geological Survey of New South Wales Bulletin 26, Sydney).

Benson, D.H. (1992). The natural vegetation of the Penrith 1:100 000 map sheet. *Cunninghamia* 2, 503-662.

Black, M.P., Mooney, S.D. and Martin, H.A. (2006). A > 43,000-year vegetation and fire history from Lake Baraba, New South Wales, Australia. *Quaternary Science Reviews* 25, 3003-3016.

Birks, H.J.B. and Birks, H.H. (1980) 'Quaternary Palaeoecology'. (Edward Arnold, London).

Boland, D.J., Brooker, M.I.H., Chippendale, G.M., Hall, N. H., Hyland, B.P.M., et al. (2002). 'Forest Trees of Australia' 4th Edition (Thomas Nelson: Australia).

BoM, (2006). Commonwealth Bureau of Meteorology Website (http://www.bom.gov.au). Accessed August 2006.

Brown, C.A. (1960). 'Palynological Techniques' (C.A. Brown, Baton Rouge) 188 pp

Bureau of Meteorology (1966). Rainfall Statistics in Australia. (Commonwealth of Australia, Melbourne)

Chalson, J.M. (1991). The late Quaternary vegetation and climatic history of the Blue Mountains, NSW, Australia. PhD Thesis, University of New South Wales (unpubl.)

Chalson, J.M. and Martin, H.A. (1995). The pollen morphology of some co-occurring species of the family Myrtaceae in the Sydney region. *Proceedings of the Linnean Society of New South Wales* 115, 163-191.

Harrison, S.P. (1993). Late Quaternary lake-level changes and climates of Australia. *Quaternary Science Reviews* 12, 211-231.

Hope, G. (1989). Climatic implications of timberline changes in Australasia from 38 000 yr BP to present. In 'CLIMANZ 3, Proceedings of the Third Symposium on the Late Quaternary Climatic History of Australasia' (Melbourne University 28-29 November 1987) pp 91-99. (CSIRO, Institute of Natural Resources and Environment).

Kohen, J.L., Stockton, E.D. and Williams, M.A.J. (1984). Shaws Creek KII Rockshelter: a prehistoric occupation site in the Blue Mountains Piedmont. *Archaeology in Oceania* 18 (2) 19 (1/2), 57-73.

Macphail, M. and Martin, T. (1991). 'Spineless' Asteraceae (episode 2). *PPAA Newsletter* 23, 1-2. (Palynological and Palaeobotanical Association of Australasia: Melbourne).

Martin, H.A. (1973). The palynology of some Tertiary Pleistocene deposits, Lachlan River Valley, New South Wales. *Australian Journal of Botany Supplement* 6, 1-57.

Moore, P.D., Webb, J.A. and Collison, M.E. (1991). 'Pollen Analysis'. (Blackwell Scientific Publications, Oxford).

Nanson, G.C. and Young, R.W. (1988). Fluviatile evidence for a period of late Quaternary pluvial climate in coastal southeastern Australia. *Palaeogeography, Palaeoclimate, Palaeoecology* 66, 45-61.

Nanson, G.C., Young, R.W. and Stockton, E.D. (1987). Chronology and palaeoenvironment of the Cranbrook Terrace (near Sydney) containing artefacts more than 40 000 years old. *Archaeology in Oceania* 22, 72-78

Penrith Lakes Development Corporation, (1983/84). Penrith Lakes Scheme Regional Environmental Study. Department of Environment and Planning, Sydney.

Penrith Lakes Development Corporation, (2006). http://www.penrithlakes.com.au Accesed June 2006.

Pickett, E.J., Harrison, S.P., Hope, G., Harle, K. et al. (2004). Pollen-based reconstructions of biome distributions from Australia, Southeast Asia and the Pacific (SEAPAC region) at 0, 6000 and 18,000 ^{14}C yr BP. *Journal of Biogeography* 31, 1381-1444.

Robbie, A. and Martin, H.A. (2007). The history of the vegetation from the last glacial maximum at Mountain Lagoon, Blue Mountains, New South Wales. *Proceedings of the Linnean Society of New South Wales* 128, 57-80.

Stockton, E.D. and Holland, W.N. (1974). Cultural sites and their environment in the Blue Mountains. *Archaeology and Physical Anthropology in Oceania* 9 (1), 36-65.

Stuiver, M and Reimer,P.J. (1986-2005). Radiocarbon calibration program Calib. Rev 5.0.2. http://calib.qub.ac.uk/calib/calib.html (accessed November 2007)

Williams, N.J. (2005). The environmental reconstruction of the last glacial cycle at Redhead Lagoon in coastal eastern Australia. PhD Thesis, University of Sydney (unpubl.).

Williams, N.J., Harle, K.J., Gale, S.J. and Heijnis, H. (2006). The vegetation history of last glacial-interglacial cycle in eastern New South Wales, Australia. *Journal of Quaternary Science* 21, 735-750.

Young, R.W., Nanson, G.C. and Jones, B.G. (1987). Weathering of late Pleistocene alluvium under a humid temperate climate: Cranebrook Terrace, southeastern Australia. *Catena* 14, 469-484.

APPENDIX 1. POACEAE POLLEN TYPES.

Poaceae type	Diameter µm	Exine thickness µm	Other characteristics
1	~35	<5	Faintly granular surface pattern, grains often crumpled
2	~30	~1.5	Smooth surface, grains retain spherical shape
3	~25x35	~1	Faintly granular surface, grains retain ovate shape, with the broad end with pore depressed
4	~35	~1	Faintly granular surface, grains retain spherical shape
5	~30	~1.5	Surface smooth, grains retain spherical shape
6	25-30	<0.5	Surface granular, grains usually crumpled

APPENDIX 2. THE IDENTITY OF *TUBULIFLORITES PLEISTOCENICUS*, ASTERACEAE

The form species *Tubuliflorites pleistocenicus* Martin 1973 was described to accommodate pollen which was identifiable with the family Asteraceae but which lacked the spines usually seen on these grains. The 'spineless' Asteraceae may be found in considerable abundance in the last glacial period pollen spectra and is less common in younger sediments. This pollen type is found in *Calomeria* and several other genera (see Chalson 1991). *Calomeria* is a shrub of high rainfall areas of Gippsland and southern New South Wales, and is found in wet sclerophyll and the margins of rainforest (Chalson 1991). Descriptions by early botanists of the species in 'scrubby brushwood' along the Nepean River, some 50 km upstream from Penrith, include *Calomeria amaranthoides* and other wet sclerophyll species (Benson 1992). However, *C. amaranthoides* is thought unlikely during the last glacial period (Zone C) which is expected to be much drier than the present.

This 'spineless' Asteraceae pollen is also found in *Cassinia arcuata* which also closely resembles *T. pleistocenicus*. *C. arcuata* is widespread across the drought and frost-prone western slopes of NSW and extends on the Central and Southern Tablelands. Moreover, it readily colonised bare and disturbed ground (Macphail and Martin 1991), a habitat which could be created by river activity on a regular basis. It is thought that *C. arcuata* was more likely during the glacial period, but *Calomeria* cannot be ruled out for Zone D (c. 35-31 ka), where there was a good forest cover, although no other wet sclerophyll species have been recorded in the pollen spectra.

APPENDIX 3. POLLEN TYPE NAME ON THE POLLEN DIAGRAM (FIG. 4) AND THE PROBABLE SOURCE IN THE VEGETATION.

Name on the pollen diagram	Probable source in the vegetation
Podocarpus	Probably *Podocarpus spinulosus*, shrub to small tree
Pinus	*Pinus* sp(p)., Introduced
Eucalyptus tereticornis	*Eucalyptus tereticornis*
E. mannnifera	*E. mannnifera*
E. viminalis	*E. viminalis*
Leptospermum polygalifolium	*Leptospermum polygalifolium*
L. juniperinum	*L. juniperinum*
Unidentified Myrtaceae	All other pollen types in the family
Casuarina	Probably *Casuarina cunninghamii,* possibly *Allocasuarina* sp(p)
Other tricolporate grains	Unidentified tricolporate grains, probably herbs and shrubs
Chenopodiacese	All taxa in the family
Acacia	All species in the genus
Haloragaceae	*Haloragis/Gonocarpus*
Asteraceae/Liguliflorae	Fenestrate taxa in the subfamily Liguliflorae
Asteraceae/Tubuliflorae	Echinate taxa in the subfamily Tubuliflorae
T. pleistocenicus	Most likely *Cassinia arcuata,* see Appendix 2
Monotoca	All species in the genus
Caryophyllaceae	Family Caryophyllaceae
Cyperaceae	All species in the family
Myriophyllym	all species in the genus
Trilete spores	Ferns
Monolete spores	Ferns
Poaceae type 1	Poaceae, see Appendix 1
Poaceae type 2	Poaceae, see Appendix 1
Poaceae type 3	Poaceae, see Appendix 1
Poaceae type 4	Poaceae, see Appendix 1
Poaceae type 5	Poaceae, see Appendix 1
Poaceae type 6	Poaceae, see Appendix 1